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TECHNICAL NOTE

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PERFORMANCE EVALUATION OF A MERCURY-PROPELLANT FEED SYSTEM FOR A FLIGHT-MODEL ION ENGINE

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PERFORMANCE EVALUATION OF A MERCURY-PROPELLANT FEED SYSTEM FOR A FLIGHT-MODEL ION ENGINE

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SUMMARY

A mercury-propellant feed system for a flight-model ion engine was constructed and evaluated for operation in vacuum facilities. The propellant feed system consisted of an electrically heated mercury boiler and a transistorized temperature controller. The boiler was constructed with a porous plug for restricting flow of vaporized mercury and preventing liquid mercury from leaving the boiler during simulated launching. Liquid mercury was retained with minor losses during simulated launching tests. The propellant feed system was capable of reaching steady-state operating conditions after $4\frac{1}{2}$ minutes of operation and maintaining the propellant flow within 9.0 percent of the desired value with the ion engine operating for 30 minutes at 0.350-ampere beam current.

INTRODUCTION

Investigations carried on in vacuum facilities have shown that a promising type of ion engine that is mechanically simple as well as reliable and efficient is the electron-bombardment engine operating on mercury vapor (refs. 1 to 4). A flight version of this engine will be used for space testing of an ion engine. The primary aims of the tests are to establish thrust generation and neutralization effectiveness in space.

The object of the study reported herein was to construct and evaluate the operation of a mercury-propellant feed system suitable for flight operation of an ion engine. Previous electron-bombardment ion engines employed a boiler held at a constant temperature by a steam jacket and used interchangeable calibrated orifices to change propellant flow conditions (ref. 4). For a flight-model version of this engine, an electrically heated boiler and a temperature controller were needed. A propellant feed system was evaluated with the mercury stored in a boiler as a liquid. The mercury is vaporized and metered to the engine by heating the boiler to the proper temperature. Liquid mercury is prevented from leaving the boiler during powered missile flight by a porous plug and baffles. The porous plug also acts as a calibrated restriction to flow of vaporized mercury. The mercury flow is controlled indirectly by regulating the temperature of the coldest part of the boiler by a feedback control loop. The steady-state boiler flow characteristics and controller operation under normal vacuum tank operating conditions are presented. The dynamics for the boiler and feedback-controlled feed system are also shown.

ION ENGINE

One version of the electron-bombardment ion engine is shown in figure 1(a). A cutaway view of this engine is shown in figure 1(b). Propellant gas is supplied to the engine from the boiler and enters the ionization chamber through a distributor. The distributor serves to proportion the propellant into the proper regions of the ionization chamber. The gas is then ionized by high-velocity electrons. The electrons are emitted by a hot filament and obtain a high velocity as they are accelerated through a plasma sheath surrounding the filament. The screen and distributor on the ends of the ionization chamber are maintained at the same potential as the filament to prevent electrons from reaching either end. The field coil serves to set up an axial magnetic field, the purpose of which is to cause the electrons to spiral in their outward path toward the anode and thus increase the probability of an ionizing collision with the propellant gas. Ions that diffuse to the screen are accelerated by an axial electric field to become the ion beam.

Operating beam currents of the order of 0.2 to 0.4 ampere might be expected in a flight-model electron-bombardment ion engine (using a 10-cm-diam. beam). If a propellant utilization of 80 percent is assumed, the boiler would be required to provide a range of 1.87 to 3.75 grams per hour of mercury vapor.

PROPELLANT FEED SYSTEM

A boiler was designed to meter mercury vapor flow to the engine and prevent liquid mercury from leaving the boiler during vibration loading. Typical vibration loading information obtained from preliminary Scout missile data is presented in table I. The mercury flow was controlled indirectly by the action of a feedback controller that maintained the boiler temperature at a constant value. It was assumed that the propellant feed system described in this report would be operated aboard a spinning vehicle in which the centrifugal force would hold the mercury against a cylindrical wall of the boiler chamber.

Mercury Boiler

The mercury boiler that was constructed and evaluated is shown in figure 2(a). A cutaway sketch is shown in figure 2(b). The boiler chamber was 2 inches in diameter and $1\frac{1}{2}$ inches long. It had a porous stainless steel plug mounted near the center and an access plug on the back plate for loading the mercury. The center location was chosen for the porous plug so that liquid mercury could not rest on its surface for any orientation of the boiler. This was necessary since it was found experimentally that, for the porous material used, the surface tension of the mercury at room temperature would prevent liquid-mercury flow only as long as the pressure differential did not exceed 3.2 pounds per square inch. Therefore, if a layer of mercury 0.130 inch in depth or greater were resting on the porous surface, it would flow through when subject to a takeoff acceleration of 50 g's.

Power was supplied to the boiler by electric current passing through resistance heaters. The heaters were distributed to minimize the temperature variation throughout the unit. The heaters were constructed of Nichrome wire that was swaged into tubing which was welded to the boiler. The tubing was capped at each end to prevent heater outgassing, which could affect engine performance. Under steady-state operating conditions the heat supplied by the resistance heaters would principally balance that lost by radiation. The heat lost by vaporization of the mercury propellant was a small percentage of the heat supplied to the boiler. Heat conducted to the residual gas within the vacuum chamber was negligible for pressures under 10^{-4} millimeter of mercury. The boiler was constructed of a low-nickel-content nonmagnetic stainless steel (type 201) to limit possible chemical reaction between the mercury and the chamber walls and to prevent distortion of the magnetic field within the ionization chamber. The normal operating temperature of the system was in the range 330° to 430° F, which represented obtainable thermal equilibrium conditions with the engine operating at temperatures of 300° F and higher near the boiler. Heat conduction from the engine to the boiler was minimized by a knife edge on the boiler flange. Higher boiler temperature operating ranges were avoided to circumvent contamination of the porous plug that would alter the propellant flow calibration. Contamination studies indicated that mercury had a tendency to react with the nickel contained in the stainless steel at higher temperatures. Mercury vapor flow to the engine was restricted by a 1/8-inch-thick plug of porous stainless steel having a mean pore diameter of 0.0008 inch. Vapor flow was permitted through a 0.425-inch-diameter section of the plug. The porous stainless steel plug in combination with a baffle mounted 1/16 inch from the plug would prevent liquid mercury from leaving the boiler during the launching of the test vehicle.

Temperature Controller

The boiler was controlled by using a feedback control system. A block diagram of the system is shown in figure 3. The circuit diagram for the system is presented in figure 4. Temperature sensing was accomplished using a thermistor embedded in the back plate of the boiler. The thermistor was used as one element of a bridge, the output of which indicated the temperature error. A set-point resistor was also an element of the bridge; its value determined the set-point temperature. The error signal was fed into a transistorized proportional amplifier that supplied current to the boiler heater. The amplifier operated with a 40-volt supply, which permitted up to 160 watts of power to the heater. For use in engine flight testing a heat sink was necessary for the rejected heat from the final stage of the transistor amplifier.

BOILER SHAKE TESTS

A mercury boiler was tested to determine its ability to retain liquid mercury under simulated launch conditions by vibration testing on an electrically driven shake stand. The baffle arrangement shown in figure 2(b) was arrived at after several preliminary shake tests on a mechanical shake table. The baffle configurations evaluated and the results of preliminary testing are presented in table II. These preliminary tests consisted of applying 1/8-inch-amplitude, 40-cps vibrations during 1 hour for several orientations of the boiler. The boiler used in the shake tests had larger mean pore diameters than the one used with the engine. A 1/8-inch-thick plug of porous stainless steel having a mean pore diameter of 0.0015 inch was used in all shake tests. A vacuum was applied to the boiler during each vibration test. The propellant loss was determined by weighing the mercury before and after each test. Configuration 5 exhibited the best mercury retention during testing and consequently was chosen for additional testing on more elaborate facilities. Typical vibration loadings chosen as a basis for the shake tests were taken from vibration loading information obtained from preliminary Scout missile data shown in table I. Some missile vibration tests have indicated higher g loading than shown in this table for several ranges of frequencies above 250 cycles per second. These higher loading levels, which reached a maximum of 41 g's, were felt to be negligible as far as propellant loss was concerned since they were observed to exist for only short time intervals.

The vibration loading tests were made with the boiler axis located both vertically and horizontally and with the vibrations applied parallel and transverse to the axis for each orientation. The boiler contained a known amount of mercury, about 50 grams, at the beginning of each test. The boiler was mounted on a vacuum chamber, which was rigidly attached to the shake stand. The boiler was then cycled through the three vibration ranges (table I), a total time of 40 minutes being spent in each range. The amplitude and frequency of the vibrations were measured by an accelerometer mounted close to the boiler. Shake-table facilities were set to run through each vibration range at a uniform rate. Constant amplitude or constant g loading was maintained automatically by feedback control, which was an integral part of the shake-table equipment. After a total time of 2 hours of vibration loading the mercury was carefully removed and reweighed to determine the amount shaken through the porous plug. Results of the shake tests are presented in table III. The losses were well below 1 percent (0.06 g) and were considered reasonable for flight.

Mercury was transferred to the boiler and then removed several times to determine the amount of mercury that might be expected to be lost in handling. The mercury loss per transfer was found to be less than 0.005 gram.

STEADY-STATE OPERATION

The mercury boiler and controller were tested in bell-jar vacuum facilities to determine their steady-state performance. The steady-state vapor flow characteristics and the temperature controller performance under engine operating conditions were both determined.

Calibration Curve

Steady-state mercury vapor flows were measured for various boiler temperatures. The resulting calibration curve is presented in figure 5, where the temperature of the access plug is used as an indication of the boiler temperature. The access plug was found to be the coldest part of the boiler, being approximately 10° F lower than the hottest points of the boiler. The coldest part was believed to determine the chamber pressure since its area was significant with respect to the area of the mercury surface. For the calibration runs, the boiler was mounted on a boron nitride disk to provide additional thermal insulation from a liquid-nitrogen-cooled condenser into which the mercury flow was directed. The boiler was carefully cleaned before the calibration runs to prevent mercury contamination because impure mercury was found to impair data repeatability. Mercury impurities formed a surface layer that affected the relation between vapor pressure and temperature. This effect was particularly noticeable at lower temperatures. For each calibration point the boiler was loaded with 50 grams of triple-distilled mercury. The access plug was replaced after loading and sealed against vapor leakage. The bell-jar vacuum system was then pumped down to a pressure below 10^{-4} millimeter of mercury, and the boiler was quickly brought up to temperature, which was held constant (at the access plug) within 2° F for 1 hour. After the boiler cooled, the mercury was reweighed. Mercury lost during the initial heating and final cooling portions was estimated by repeating this part of the run. An approximate fit to the calibration data presented in figure 5 was obtained with a mass-flow equation of the form

$$m = \frac{KP}{\sqrt{T}} \tag{1}$$

where

m mercury vapor flow

K proportionality constant

P mercury vapor pressure corresponding to temperature T

T absolute access plug temperature

Equation (1) can be used, with different constants, for either free molecular flow or choked continuous flow if, as for mercury, the ratio of specific heats is independent of temperature. The actual flow through the porous plug was probably within the slip-flow region between the two types since the mean free path of the mercury particles within the boiler chamber varied from about 0.0004 to 0.00005 inch at temperatures from 310° to 450° F. An adequate approximation was the assumption that the same form of equation prevailed within this slip-flow region, as shown in figure 5.

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Controller Operation

The mercury boiler was mounted on the ion-bombardment engine and installed in a large vacuum facility as shown in figure 6. The vacuum facility is fully described in reference 5. It consisted mainly of a 16-inch bell jar attached to a 5- by 16-foot cylindrical tank evacuated by three 32-inch diffusion pumps. Vacuum-facility pressure was maintained below 10^{-4} millimeter of mercury during controlled operation.

The propellant system was operated without power applied to the engine. After steady-state conditions had been reached, the boiler temperature drifted approximately 1° F from a desired value over 30 minutes of propellant system operation. This drift was primarily due to temperature variations in the controller components.

With the engine operating at 0.350-ampere beam current, the controller was set to maintain 3.37 grams of mercury per hour to the engine corresponding to a boiler temperature of 360° F. After about $4\frac{1}{2}$ minutes of controller operation, the boiler temperature reached steady-state conditions. The engine was then turned on and operated for a period of 30 minutes, during which the temperature of the boiler rose 4° to 364° F because of the thermal disturbance from the engine on the propellant feed system. Engine temperature measured near the boiler rose from 345° to 445° F over the engine operating period. The engine temperature rise was a result of the long time needed for the engine to reach a thermal equilibrium (approx. 1 hr). The propellant flow to the engine was increased 9.0 percent from the desired value during engine operation. This flow control was felt to be sufficient for preliminary ion-engine testing.

Engine sparking and breakdown, which are common during an initial period of engine operation, proved to be serious detriments to controller life. It was necessary to protect the controller against these surges and to eliminate as much as possible the capacitance between the controller, which was at engine potential (2500 v), and ground.

The proportional controller provided adequate temperature control for preliminary ion-engine testing. If a more accurate mercury flow is required, a controller with integral control might be considered in order to eliminate the steady-state temperature error.

SYSTEM DYNAMICS

The boiler temperature response was obtained experimentally for the boiler alone and for the closed-loop system. In each case the output response was recorded after the input was given a small step change. Boiler radiation in each case was to room temperature.

Experimental Boiler Temperature Response

The open-loop temperature response for the boiler was determined by applying a step change in power to the heater and recording the subsequent change in temperature. The temperature of the boiler was initially at 400° F. The system appeared to be fairly linear over the range of interest for boiler operation, and it was felt that the response near 400° F was a good representation of the response elsewhere in the range. Figure 7 shows the temperature response of the outer edge of the back plate for a 0.3-volt change in heater voltage. The response of the access plug was of the same form as that of the boiler edge with the exception of a transmission lag, which was of the order of 20 to 50 seconds.

Temperature was measured with a thermistor that was embedded in the back plate of the boiler. The response of the thermistor alone was determined by heating the thermistor electrically by applying a known voltage to its terminals. Upon removal of the voltage, the thermistor resistance was measured as a function of time. From these data the dissipation and time constant of the thermistor were determined. For several thermistors the range in dissipation constants was 3 to 5 milliwatts per $^{\circ}F$, and the range in time constants was 0.25 to 0.35 second. The open-loop response was therefore determined almost entirely by the boiler dynamics because the time constants associated with the boiler were several orders of magnitude larger than the thermistor time constants.

Experimental Closed-Loop Temperature Response

The thermal time lag associated with the access plug would not permit stable operation of the system using a proportional controller having the gain necessary to give the desired control accuracy. Compensation for the slow response was not practical because of the large components that would be necessary. The access-plug temperature was controlled indirectly by controlling the temperature of the outer edge of the back plate. The difference in temperature between the access plug and the outer edge of the boiler was about 7° F at steady-state conditions over the region of interest on the calibration curve.

A block diagram of the control system is shown in figure 3. The boiler temperature changed 35° F for a 1-volt change in heater voltage when the boiler was radiating to a surface at room temperature. The gain of the amplifier was such that a 1° F change in the temperature of the thermistor would change the heater voltage by 12 volts. Thus the total loop gain was approximately 420.

The closed-loop system response was found by applying a step change in the set point resistance and measuring the change in heater voltage. The heater voltage was proportional to the error signal. Figure 8 shows the closed-loop temperature response for a set-point step corresponding to 0.2° F.

The initial heating curve for the closed-loop system was also obtained and is shown in figure 9. This curve was obtained by measuring the temperature of the access plug with a thermocouple after the system had been turned on. Steady-state operating conditions were reached after $4\frac{1}{2}$ minutes of operation.

SUMMARY OF RESULTS

A mercury-propellant feed system suitable for a flight-model ion engine was constructed and evaluated for engine operation in vacuum facilities. It was found that a porous plug of stainless steel could be used to restrict flow and prevent liquid mercury from leaving the boiler under simulated launching conditions. Consistent mercury flow calibration was obtained when the boiler was constructed of a low-nickel-content stainless steel to reduce mercury contamination over the operating temperature range of interest. The mercury vapor flow through the porous restriction was proportional to pressure divided by the square root of temperature. An equation of this form was used to fair the experimental data.

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Boiler shake tests indicated a baffle arrangement that was adequate for the retention of mercury for various vibration loading conditions that might be present during takeoff conditions. The mercury lost over any of several 2-hour vibration tests was 0.06 gram or less, or approximately 1 percent of the mercury that would be used during a comparable period of engine operation.

The proportional controller brought the boiler from room temperature to operating temperature within $4\frac{1}{2}$ minutes and maintained the boiler temperature within 4° F during 30 minutes of engine operation at 0.350-ampere beam current. Mercury flow was maintained within 9.0 percent.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, January 24, 1962

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2. Kaufman, H. R., and Reader, P. D.: Experimental Performance of Ion Rockets Employing Electron-Bombardment Ion Sources. Preprint 1374-60, Am. Rocket Soc., Inc., 1960.

3. Reader, P. D.: Experimental Effects of Scaling on the Performance of Ion Rockets Employing Electron-Bombardment Ion Sources. Paper presented at Nat. IAS-ARS Joint Meeting, Los Angeles (Calif.), June 1961.

4. Reader, Paul D.: Investigation of a 10-Centimeter-Diameter Electron-Bombardment Ion Rocket. NASA TN D-1163, 1961.

5. Keller, Thomas A.: NASA Electric Rocket Test Facilities. Paper R-25, Nat. Vacuum Symposium, 1960.

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TABLE I. - SCOUT MISSILE VIBRATION

LOADING DATA

Frequency, cps	Double amplitude, in.	Vibratory acceleration, g's
8 to 27.5	-----	1.3
27.5 to 52	0.036	---
52 to 500	-----	5.0

TABLE II. - PRELIMINARY MERCURY BOILER SHAKE TESTS

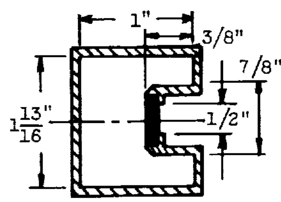
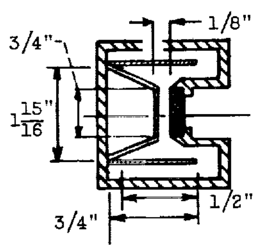
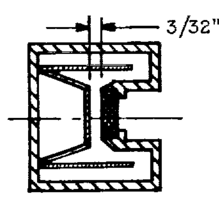
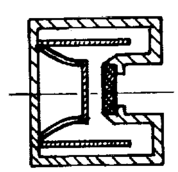
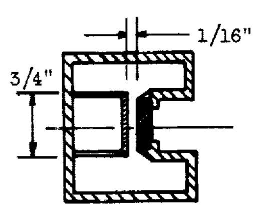
Config-uration	Sketch	Description	Range of mercury lost during 1/8" amplitude 40-cps shake tests, g/hr
1		No splash baffles used	0.5 to 10.767
2		3/4" Diam. disk mounted 1/8" from porous plug; $1\frac{5}{16}$" diam. cylinder mounted 1/4" from wall on four 1/4" wide legs; chamber dimensions same as configuration 1	2.8 to 5.6
3		Same as configuration 2 except for spacing between disk and porous plug	0.72 to 1.27
4		Same as configuration 2 except for curvature of supporting legs	6.2 to 4.08
5		3/4" Diam. disk mounted 1/16" from porous plug on four 1/4" wide legs; chamber dimensions same as configuration 1	0.004 to 0.012

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TABLE III. - SHAKE TEST OF MERCURY BOILER CONFIGURATION 5

Boiler axis orientation	Vibration direction relative to boiler axis	Loading during 8- to 27.5-cps 40-min cycle, g's	Amplitude during 27.5- to 52-cps 40-min cycle, in.	Loading during 52- to 500-cps cycle, g's	Boiler pressure, microns	Initial amount of mercury in boiler, g	Mercury lost during vibration cycles, g
Horizontal	Transverse	1.3	0.036	5.0	32	50.72	0
Vertical	Parallel	1.3	.036	5.0	37	49.18	.03
Horizontal	Parallel	1.3	.036	5.0	38	49.99	.06
Vertical	Transverse	1.3	.036	5.0	38	50.00	.04
Vertical	Transverse	13.0	.300	40.0	36	50.00	.03
Horizontal	Parallel	13.0	.300	25.0	48	50.01	.06
Horizontal	Transverse	13.0	.300	25.0 to 50.0	48	50.00	.01

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(a) Flight model.

Figure 1. - Electron-bombardment ion engine.

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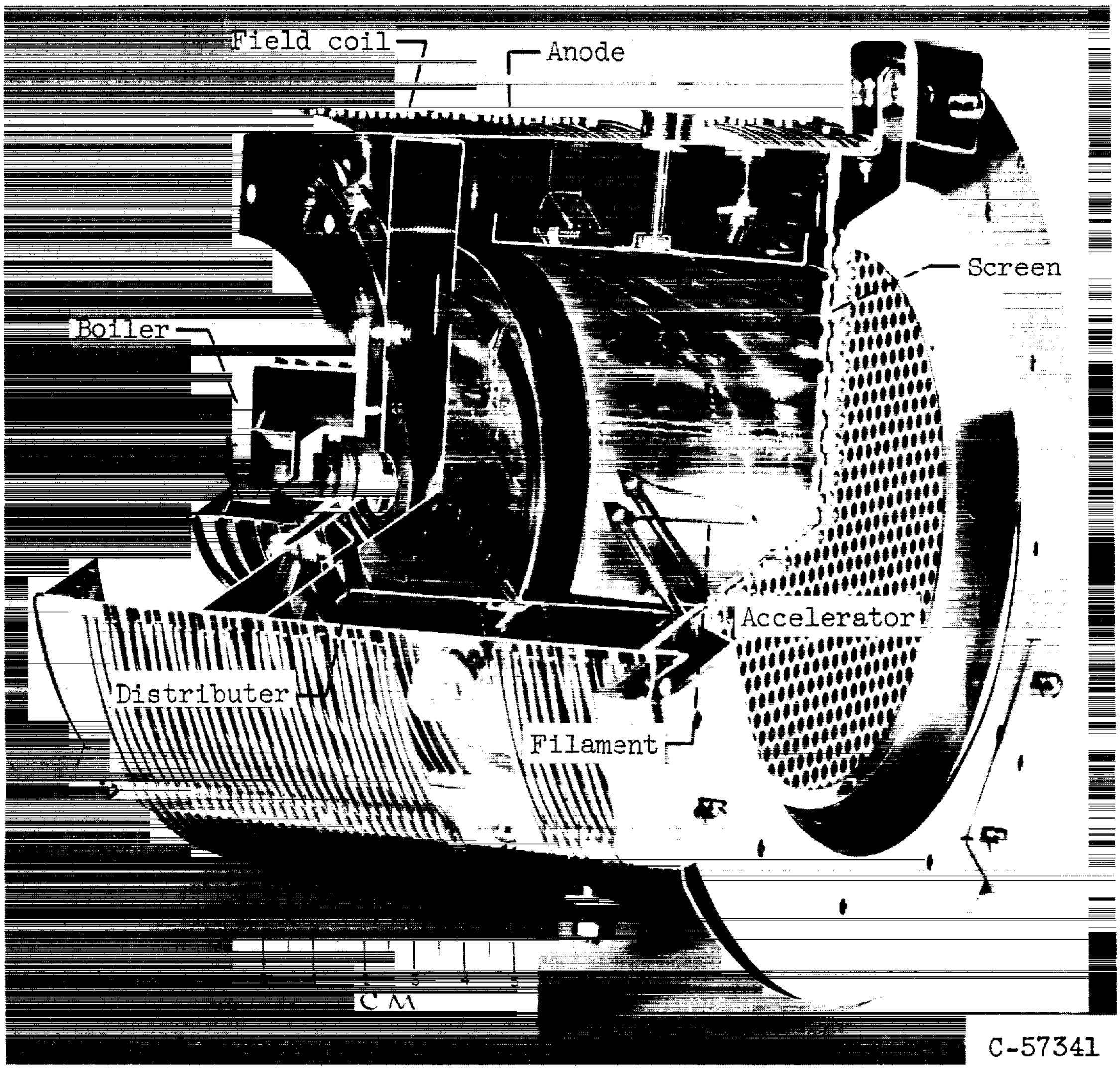
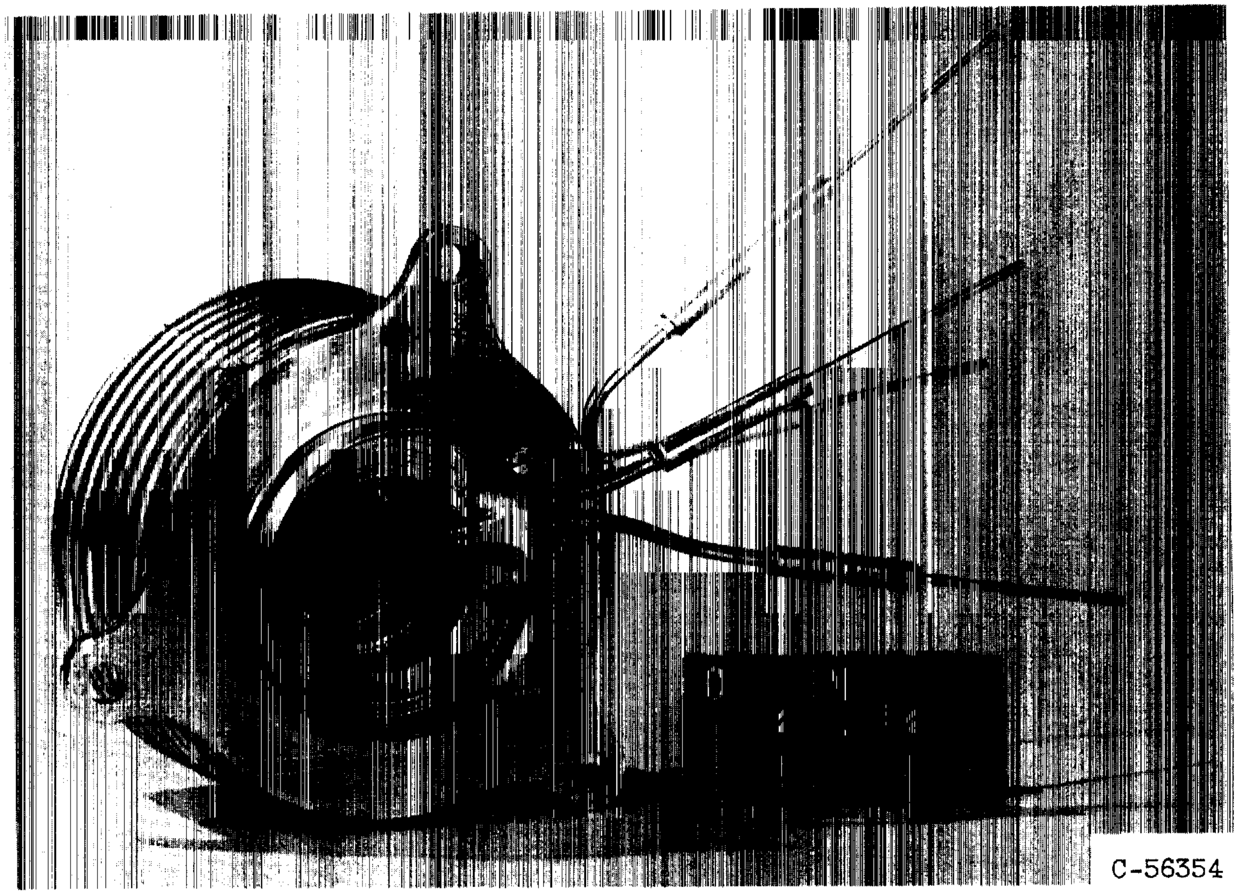


(b) Cutaway.

Figure 1. - Concluded. Electron-bombardment ion engine.



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(a) Front view.

Figure 2. - Mercury boiler.

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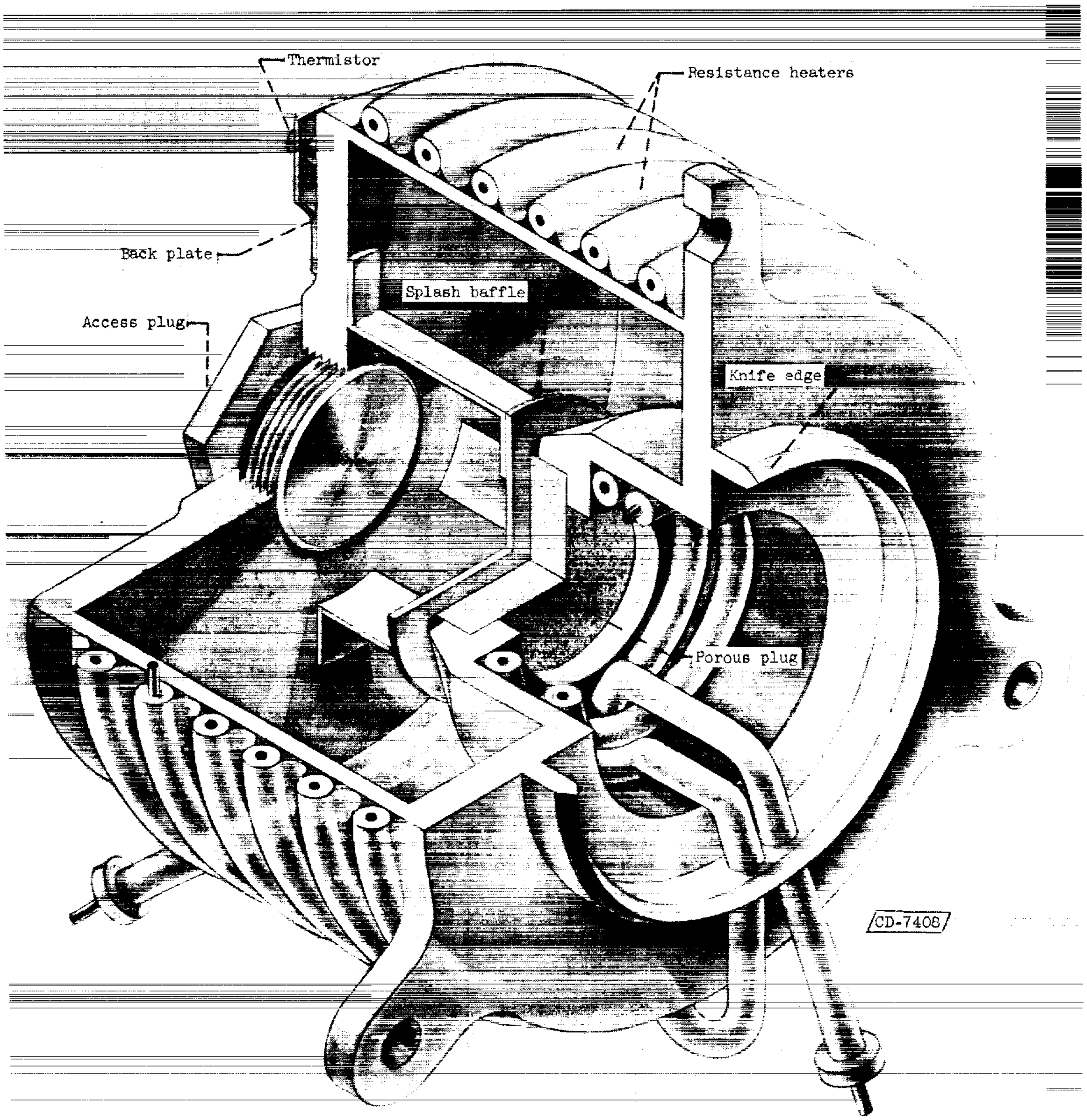

(b) Cutaway drawing.

Figure 2. - Concluded. Mercury boiler.

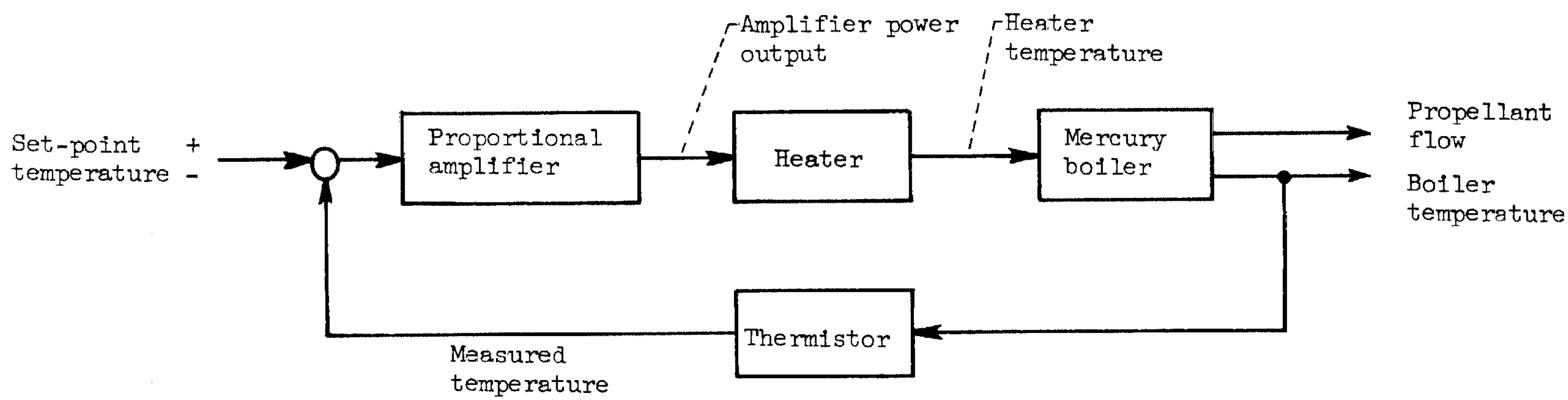

Figure 3. - Block diagram of mercury-propellant control system.

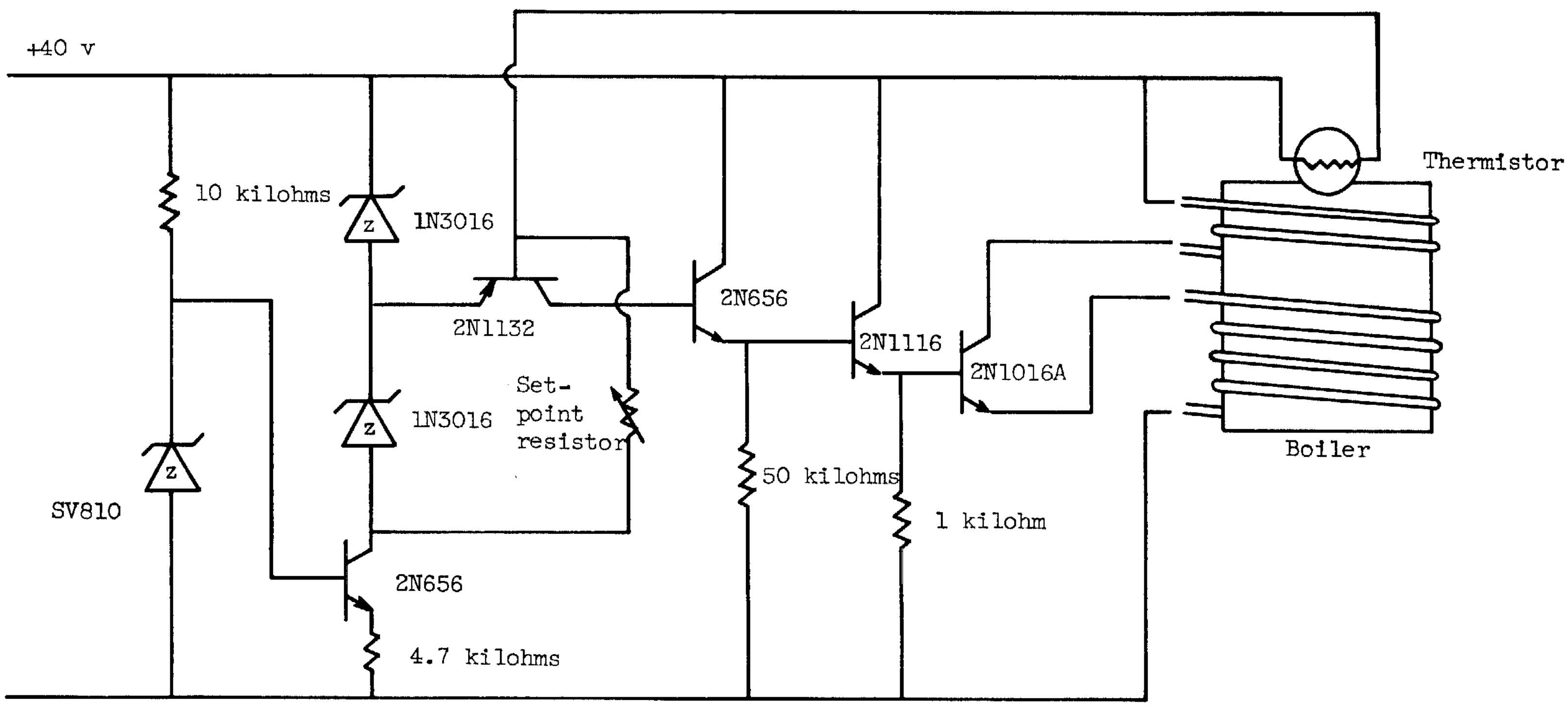

Figure 4. - Temperature controller circuit diagram.

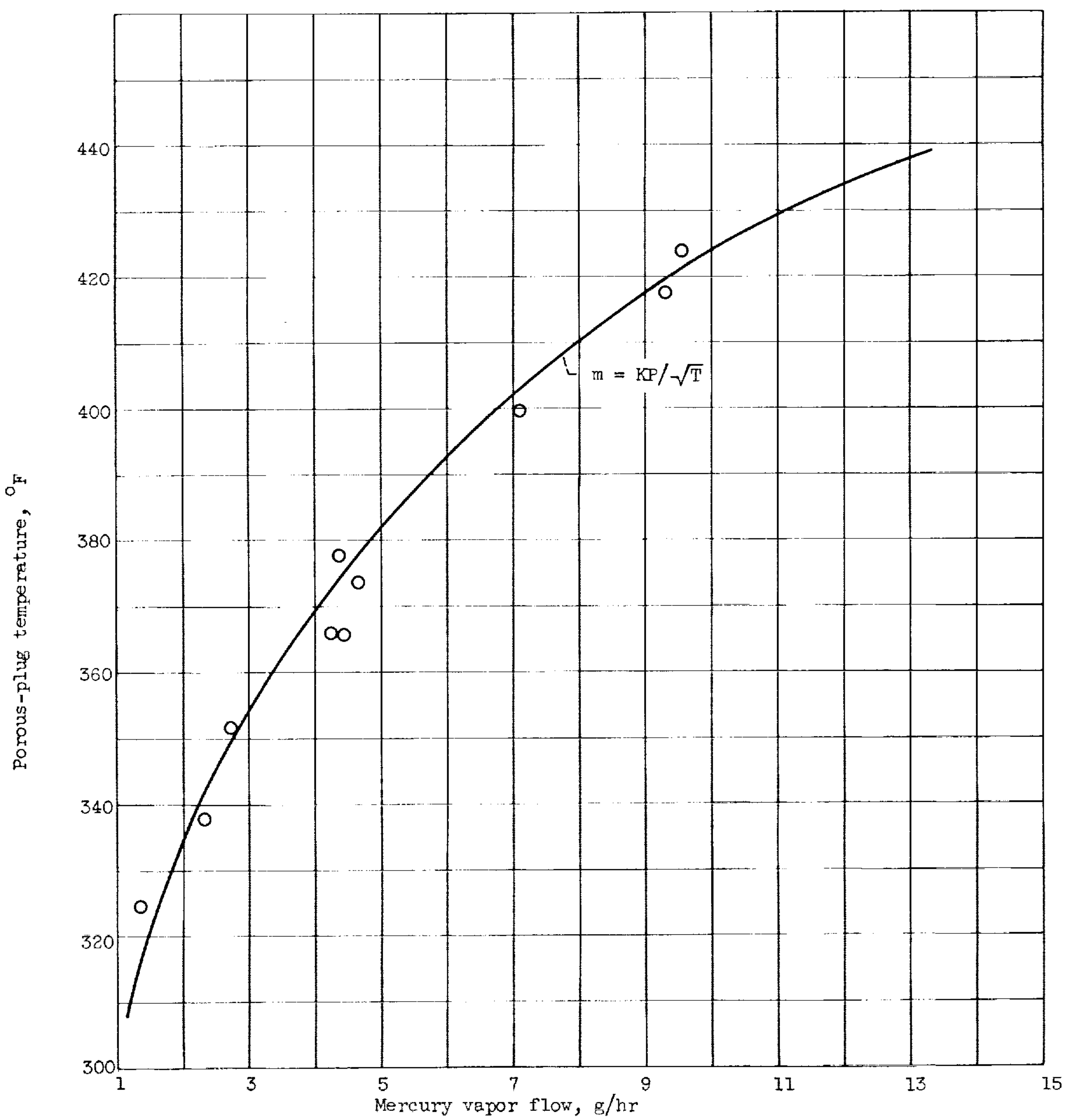

Figure 5. - Calibration curve for porous plug. Mean pore diameter, 0.0008 inch.

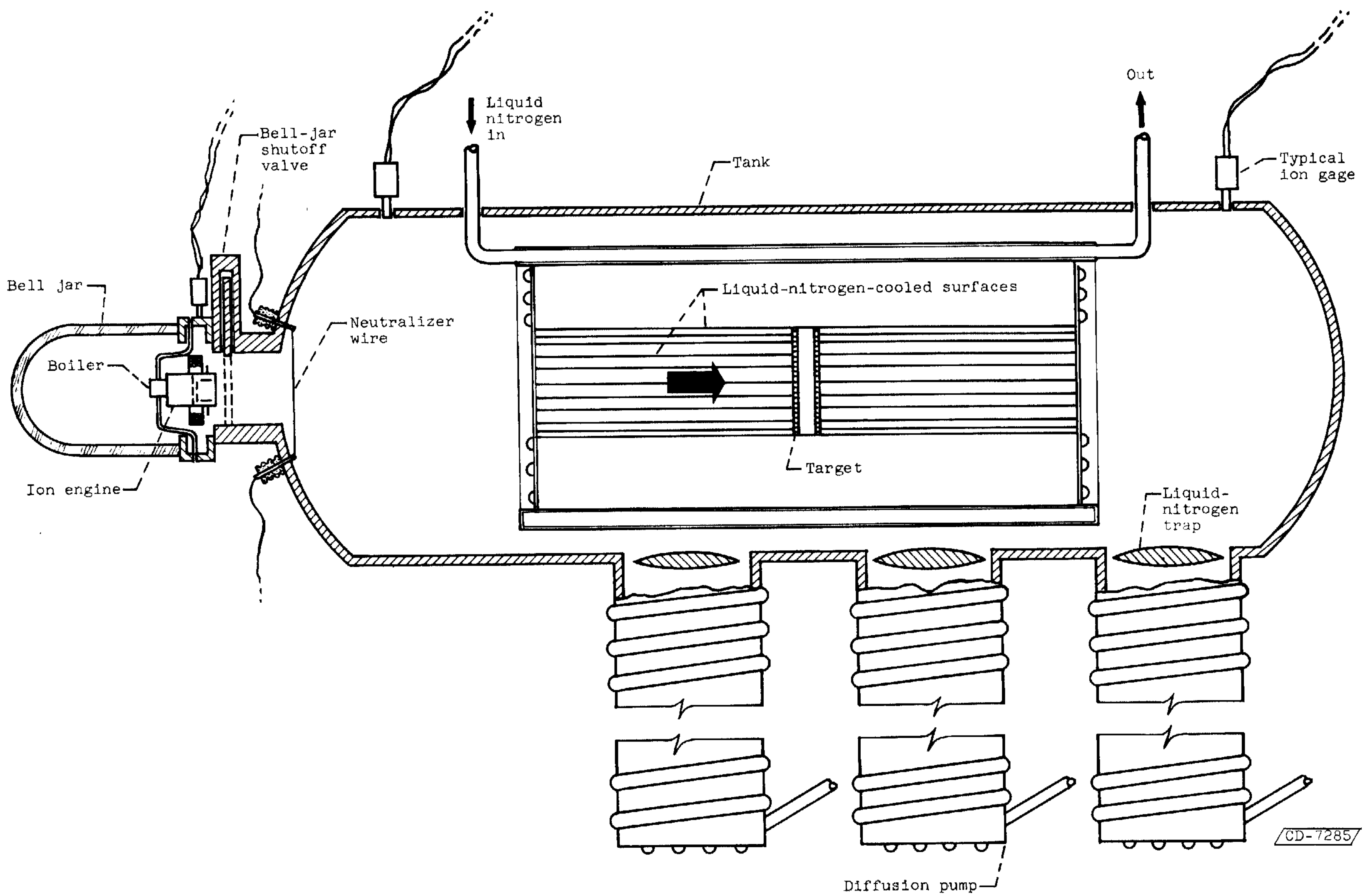

Figure 6. - Sketch of ion-engine installation and vacuum-tank facility.

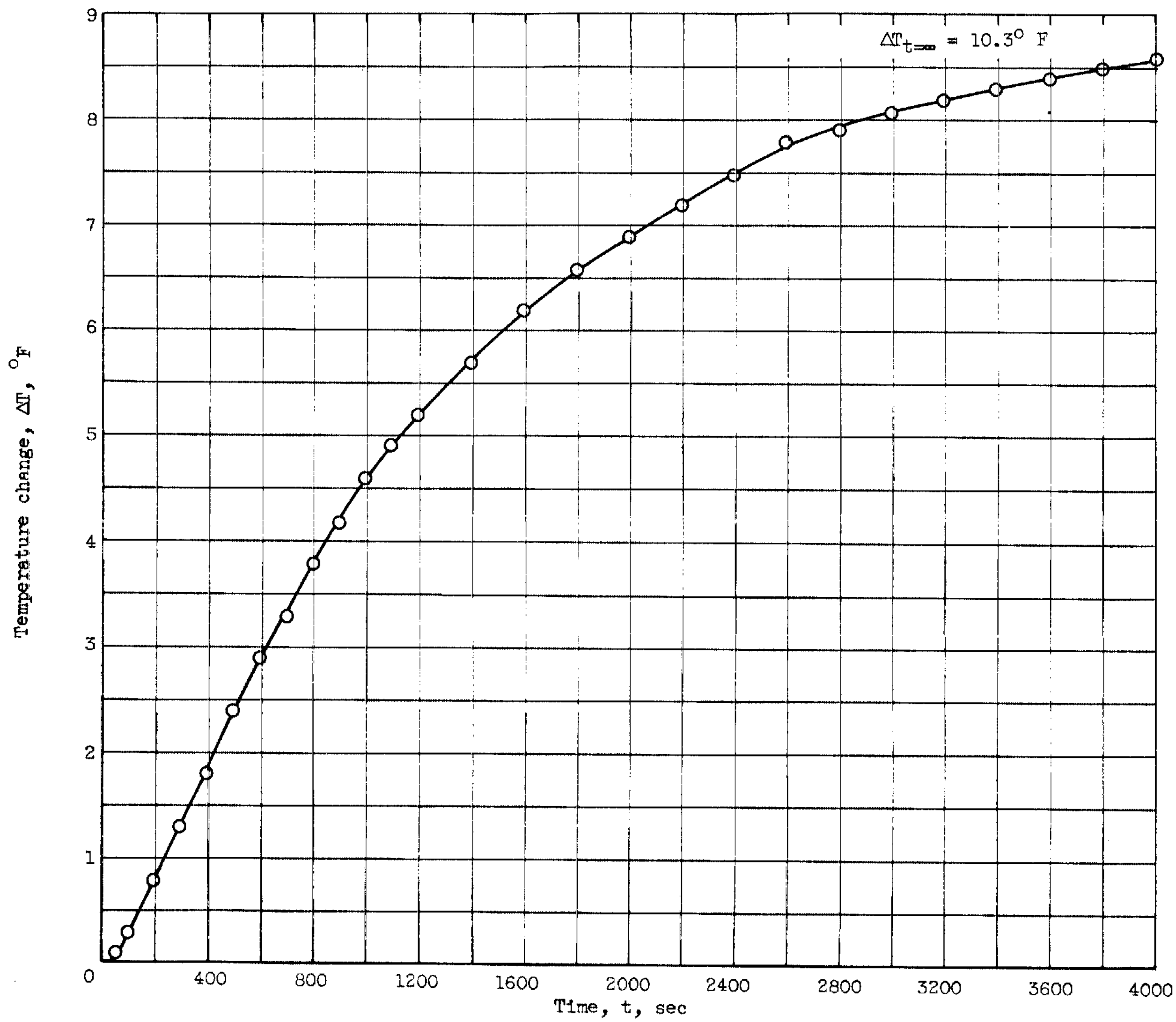

Figure 7. - Open-loop response of boiler temperature to step change in heater voltage. Initial temperature, approximately 400° F; change in heater voltage, 0.3 volt.

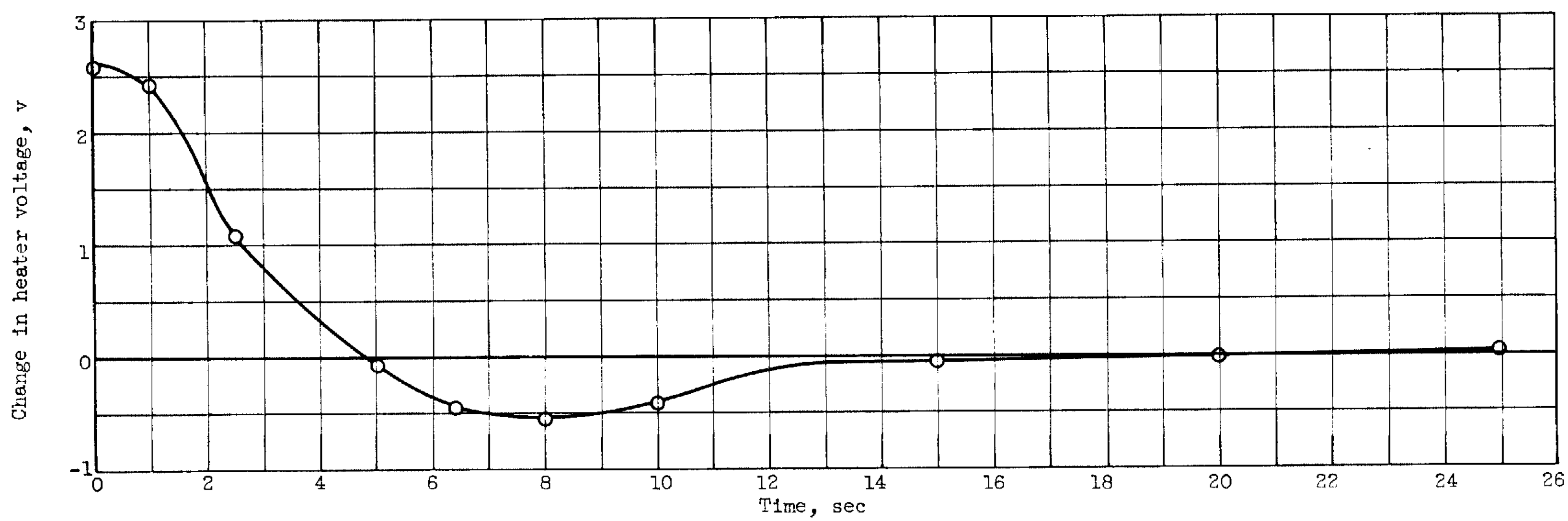

Figure 8. - Closed-loop system response to set-point step of 0.2° F. Initial temperature, approximately 400° F.

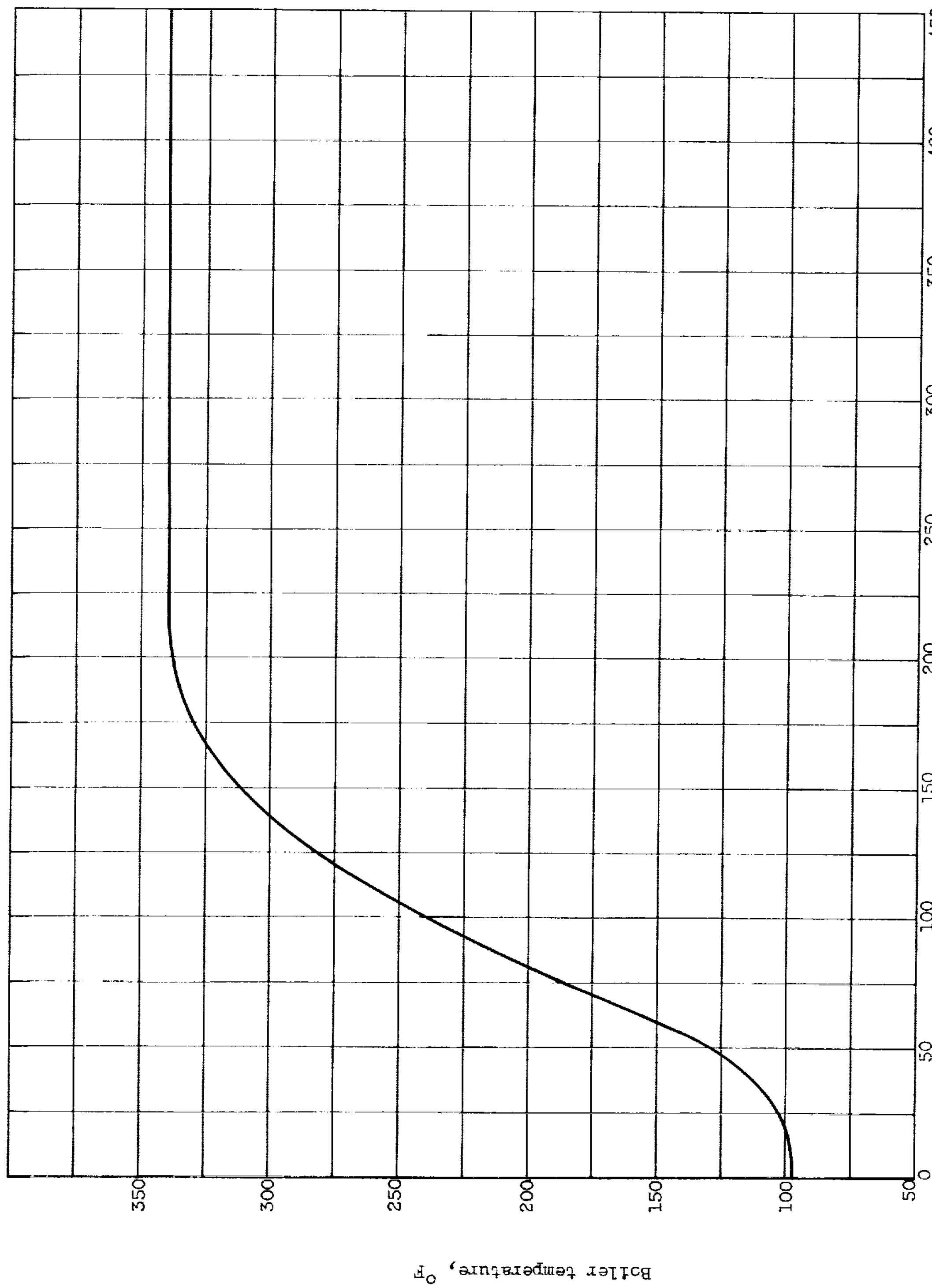

Figure 9. - Heating curve for boiler access plug with engine not operating. Vacuum chamber pressure, less than 10^{-4} millimeter of mercury.

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